Contribution to diagnosis of alkali-silica reaction in a bridge structure

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ABSTRACT: This paper describes an examination of concrete cores drilled from an old motorway bridge that had manifested deterioration and was in need of repair. Site observations and the nature of cracking indicated that alkali-silica reaction was suspect. Cores taken from the damaged structure were analyzed by using optical petrography for potential presence of reactive phases in aggregates, and chemical analyses to estimate the residual alkali content in the concrete. Results from the test methods were consistent with existence of alkali-silica reaction damage mechanism in the concrete. The level of severity of alkali-silica reactivity appeared to be moderate. The diagnostic features determined from tests indicate with some certainty, that alkali-silica reaction might have partly or solely contributed to distress in the bridge structure.

1 INTRODUCTION

Several techniques and methods are now available for diagnosing the presence of alkali-aggregate reaction in concrete, developed through concerted research over the years since Stanton, 1940 first identified the mechanism 70 years ago. Interest was also driven by increasing field experiences and reports in several countries around the world. In certain regions, the mechanism cannot be avoided as the only locally available aggregates are reactive. As concrete assumed dominance in construction and infrastructure systems, the industry by default undertakes national economic and social contributions that rely on performance and durability of concrete as a material. Alkali-aggregate reaction has gained prominence against this backdrop. In South Africa, the mechanism was first reported in the 1970's in the Cape Penisula (now Western Cape). Presently, the damage mechanism is known to exist in areas of South Western Cape, Eastern Cape, and Gauteng.

Faced with diagnosing the mechanism during forensic analysis, two challenging issues of general nature have to be considered by the expert viz;- (1) selection of the method(s) to be used, and (2) practical limitations on availability of samples and/or site information. With the range of methods and techniques available, some of which are overlapping, it can be tempting to apply a number of them. Certainly more confidence in a result is garnered with collection of consistent information from several independent tests. But practical considerations may require a focused approach which will involve selected key methods sufficient to provide confirmatory or detailed conclusive information. In this regard, it helps to first revert to understanding of damage process of alkali-aggregate reaction.

Alkali-silica reaction (ASR) is an expansive damage mechanism which occurs when reactive silica phases in certain aggregates combine with alkalis available in sufficient amounts in cementitious materials, usually Portland cement. The product of this reaction is alkali-silica gel, which imbibes water resulting in expansion and subsequently, cracking of concrete. In severe cases, ASR is manifested by map cracking and exuding of gel through cracks. The necessary conditions therefore are the presence of reactive aggregate, sufficient amount of alkalis, and moisture conditions (Fulton's, 2001; Famy & Kosmatka, 1997). In most structures, exposure to at least a certain minimum level of moisture is unavoidable and therefore this condition plays little or no role in diagnosis. It follows that most diagnostic techniques are based on detection of the presence of reactive phases, amount of available alkalis or expression of their combined effect such as presence of gel or expansion.

Experts are also usually faced with limited availability of site information. Quite often, samples from a deteriorated structure are supplied to expert for forensic analysis but little accompanying useful information may be availed to aid the investigation, viz:- age of structure, materials and their sources, methods of construction, site conditions, features of

deterioration, records, repair history, and other relevant information. This may be due to problems of site access anywhere from site control to difficult and unsafe locations within the structure or an issue of cooperation by parties involved. Sometimes, there are other reasons for which an expert is not able to have sufficient supply of information needed for diagnosis and may have to work with what is available, perhaps one or two chunks of concrete supplied with no other helpful information of site conditions. Petrographers experience these situations quite commonly. In such scenarios, the techniques employed are in part dictated by size and type of samples available.

The work presented in this paper was conducted to determine suspected presence of ASR in a motorway bridge in Gauteng located along the Johannesburg to Pretoria N1 national highway and lies in a belt where quartzites are the predominant aggregate type, perhaps of the Pretoria Group or Witwatersrand Supergroup. Pretoria Group quartzites are known to be non-reactive (Hippo, 1989) leaving the Witwatersrand quartzite as the possible culprit. History is documented of ASR-damaged concrete structures attributed to the Witwatersrand quartzite. (Blight et al., 1981; Blight et al., 1989; Hippo Quarries, 1989; Blight & Alexander, 1985; Ballim & Silbernagl, 2005). The bridge from which core samples were extracted had shown significant cracking and was in need of repair. The approach used in the analysis relates to importance of a complementary but minimal and not necessarily overlapping employment of traditional techniques for ASR diagnosis.

2 SAMPLES AND TECHNIQUES

Cores of 90 mm and 200 to 300 mm length extracted from the bridge were used for examination of concrete using laboratory techniques. Petrographic and chemical methods were employed in the analysis to detect the presence of ASR. The rationale was to utilize petrography to detect the presence of ASR in two ways:- (1) examining the aggregates used in concrete for potential reactivity, (2) possible presence of ASR gel product and reaction rims. The chemical methods on the other hand would provide complementary information from concrete mix design to be used to evaluate availability of sufficient alkali contents in the mix necessary to produce disruptive ASR in the concrete. Ultrasonic pulse velocity (UPV) test was also done to assess cracking and voidage, its severity and general soundness of the concrete examined.

2.1 Visual examination and stereomicroscopy

Prior to detailed petrographic examination, visual inspection is typically done in conjunction with a stereomicroscopic examination to first observe concrete features under low magnification. At this stage, observations are made on sample condition, material characteristics including aggregate types and sizes, pores and cracks; unusual features such as discolouration, deposits in existing cracks or pores. The large cores were saw cut to manageable sizes and examined using SWIFT model EIGHT EIGHTY stereomicroscope under 20X magnification factor. At this point areas of interest were identified, marked and saw cut for thin section preparation.

2.2 Petrography

Optical petrography is one of the most powerful traditional techniques capable of providing detailed and conclusive information about existence of ASR or its potential risk in concrete. Fundamentally, the technique reveals unique textural details which characteristically identify with a specific mineral or rock. With experience, these and other relevant information can be captured quite quickly. Examination is done using thin sections of 25 to 30 μm thickness, prepared from locations sawed at identified strategic areas and mounted on 25 x 45 mm glass microscope slide. In this study, the thin sections were examined using research grade optical microscope, NIKON OPTIPHOT-POL with high resolution imaging capabilities and up to 400X magnification. Figure 1 gives the different orientations at which thin sections were made at selected locations of core samples. Procedures outlined in ASTM C 856 “Standard practice for petrographic examination of hardened concrete” were followed in examination of the thin sections.

2.3 Chemical methods

Whereas the detection of reactive aggregates or ASR gel reaction product can be considered the most essential features suggestive of ASR attack, a more complete picture can be assembled with further details associated with alkali content of the mix. Chemical analysis is the most standard method used for this purpose. Hardened cement paste recovered from samples were analysed in accordance with BS 1881: Part 124 “Methods for analysis of hardened concrete” for ‘residual’ alkali content. Samples were broken into lumps and mortar separated from the coarse aggregates.

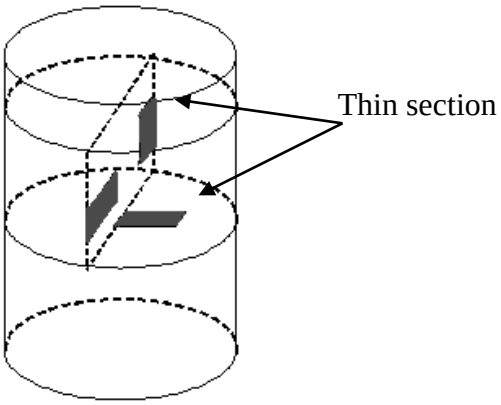

Figure 1. Orientations of thin sections prepared from concrete core samples.

Lumps of mortar were further broken then ground gently with a force sufficient to separate the sand fractions from paste without crushing sand particles. The ground samples were passed through a 90 μm sieve to obtain powdered hardened cement paste used for chemical determinations.

3 OBSERVATIONS AND ANALYSIS

3.1 Visual inspection, UPV and stereomicroscopic examination

The cores examined were generally in sound condition indicating strong concrete with fairly good paste-aggregate bond. The propagation ultrasound speed ranged from 3970 to 4430 m/s, an average of 4200 m/s indicating normal quality concrete not severely affected by cracking (see also Table 1, UPV). Aggregates consisted of crushed stone of maximum size 26.5 mm and evenly distributed sub-angular sands of sandstone or quartzite conglomerate. The cement paste colour on broken concrete surface was mostly grey but occasional white spots in certain areas were clearly visible. Also, there appeared to be some white reaction rims around some of the aggregate particles exposed at the fracture surfaces of cores. Voids were not prominent, estimated to be around 0.5% excess voidage based on BS 1881: Part 120 "Method for determination of the compressive strength of concrete cores". No evidence of pore filling was seen. At the top finished surfaces of the cores, there were no cracks observed but evidence of internal cracking was present at some aggregate-paste interfaces with cracks running through some of the coarse aggregates. The coarse aggregates showing visible cracking were found at least 100 mm from the core surfaces. These cracks were orientated sub-parallel to the direction at which cores were taken.

Examination of the core surfaces with low magnification stereomicroscope revealed presence of a transluscent gel at the interface of some coarse aggregates and the surrounding mortar. When observed by unaided eye, the feature exhibited sight of permanent dampness along the stone-mortar interface. Close examination at 10X magnification clearly showed it to be an extrusion of a colourless gel product lining the interface.

3.2 Optical microscopy

Thin sections prepared from cores were examined by optical microscopy under plane-polarized light (PPL) and cross-polarized light (XPL) to confirm the potential presence of alkali-silica reaction. Coarse aggregates were mostly quartz and the fine aggregates predominantly consisted of minerals of quartz, plagioclase feldspar and microline. Optical examination indicated a presence of reactive and potentially reactive aggregates consisting of optically *strained* quartz with undulatory extinction, *microfractured* and *microcrystalline* quartz grains. These mineral characteristics are indicative of the presence of alkali-silica reaction under appropriate conditions. Photomicrographs of these optical features are shown in figures 2 to 7. Figure 2 shows two *strained* quartz grains exhibiting the dark regions (D) and light regions (L) within the same grain under cross polars. Non-reactive aggregates undergo straight extinction changing to either uniformly dark or uniformly bright under cross-polars as the stage is rotated through 360ºC. A highly strained grain is also shown in figure 3 exhibiting similar characteristics described. Several of the reactive grains were observed in fine aggregates. Some quartz grains were severely *sutured* along individual grain boundaries. This can be seen in figure 4 but in addition, a distinctive map crack is clearly visible tending to peel off at the longitudinal edge of the crystal. Parts of the crystal appear to have undergone or to be in a process of possible chemical alteration. When the crystal in figure 4 was viewed under cross-polars, it was found to be *microcrystalline* and highly strained as seen in figure 5. Microcrystalline grains were also clearly observed in several aggregate particles such as given in figure 6 shown in cross polars. Microcrystallinity was yet another characteristic feature evident of the potentially reactive aggregates used in the concrete. In figure 7, a fractured quartz crystal shows typical ASR crack pattern and exhibits a three-way undulatory extinction along the cracks. This suggests that the crystal might be reactive and the observed cracks may be due to ASR. A *yellowish-brown staining* seen within the cracks may be either ASR gel or epoxy staining but considering that fracturing occurred along strained crystal lines, it is possible or even likely that expansive pressure forces emanated along the observed crack paths. This implies that the brown-stained fracture infilling could be ASR gel responsible for the observed

cracking. Besides, the brown staining was not quite common in other quartz crystals.

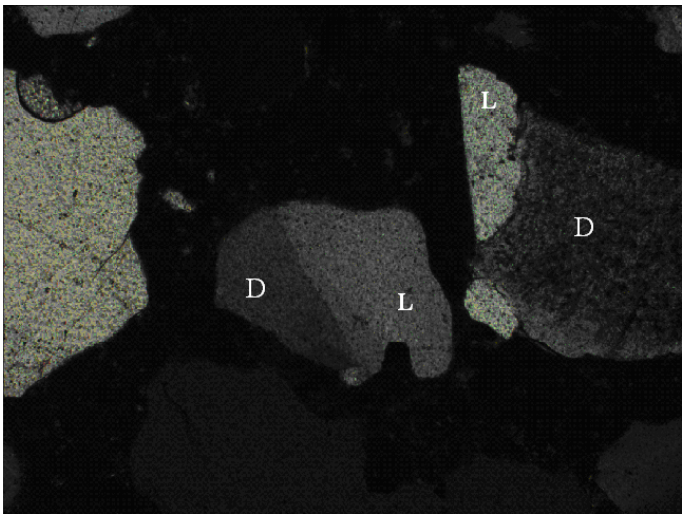

Figure 2. Strained quartz grains in potentially reactive aggregates, XPL, 100X.

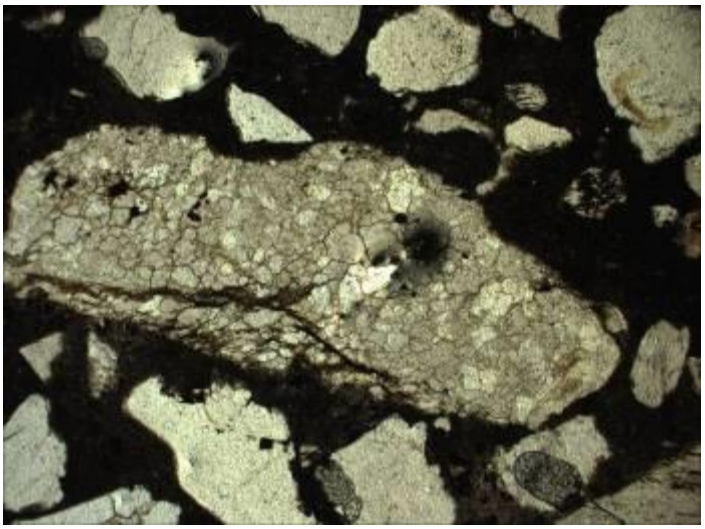

Figure 4. Sutured quartz grain contacts, enhanced visibility between individual boundaries, parts of the grain appear to be undergoing chemical alteration, PPL, 50X.

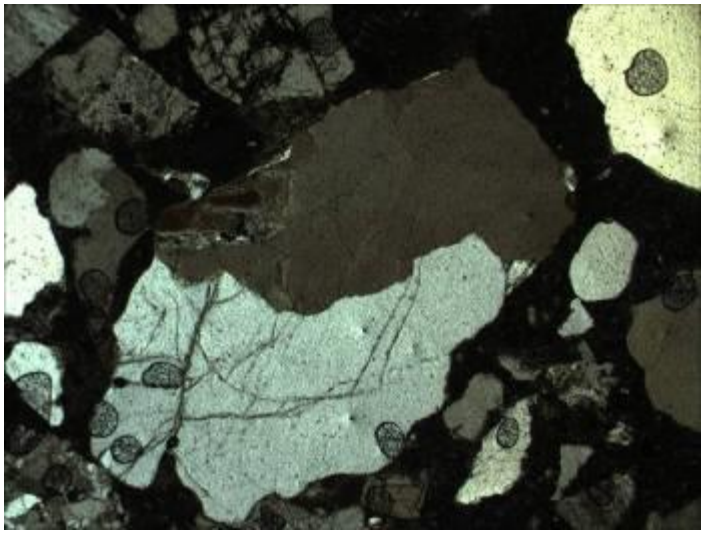

Figure 3. Highly strained quartz grain exhibiting dark and light bands within the same grain, XPL, 50X.

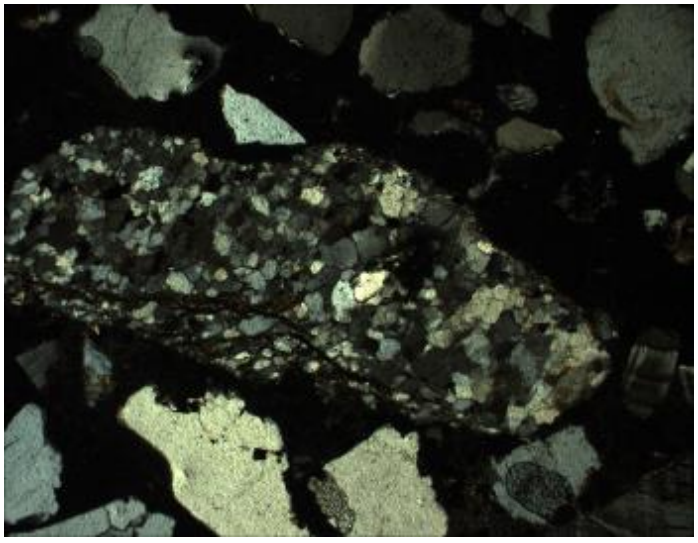

Figure 5. Same as fig. 4 but in cross-polar, microcrystalline and strained quartz, XPL, 50X.

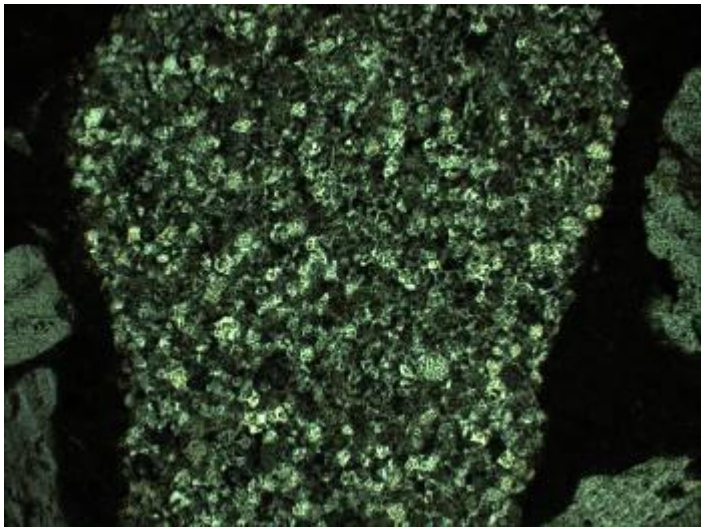

Figure 6. Microcrystalline quartz crystal XPL, 100X.

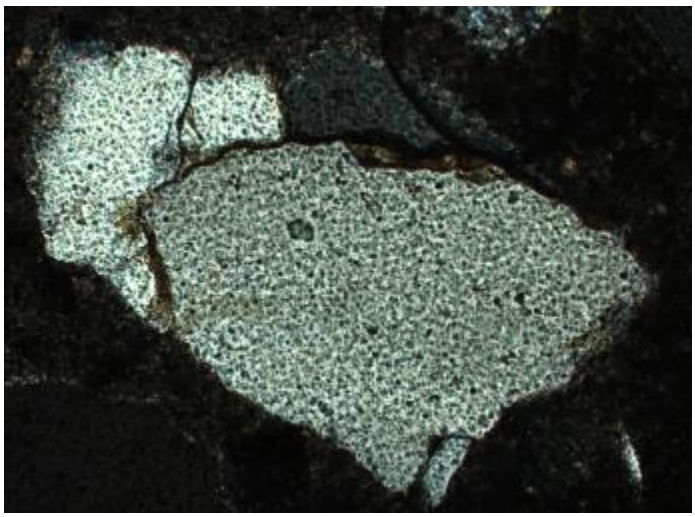

Figure 7. Fractured quartz showing a three-way undulatory extinction along the cracks infilled by yellowish-brown staining, XPL, 200X.

3.3 Alkali content

Alkali extraction was performed to estimate the present quantity of alkalis available in the hardened cement paste. Its determination is of interest in assessing the original alkali content but more importantly, these results are essential for prognostic evaluation of future potential ASR risk. Limits of Na_2O_e < 3 kg/m^3 in concrete and < 0.6% Na_2O_e in cement are required to minimize the likelihood or avoid the possibility of ASR (Famy & Kosmatka, 1997; Fulton's, 2001). This is consistent with use of low alkali cements normally considered to contain 0.3 to 0.4% Na_2O_e. In late 1970's, the Na_2O_e of cements in Gauteng (then Transvaal) province ranged from 0.55% to 0.85% with most lying below 0.64% (Oberholster, 1981). Alkali content of cements were also below 0.6% Na_2O_e between 1985 to 1998 but increased again to between 0.6% to 0.8% Na_2O_e in around 1998 (Fulton's, 2001).

In this investigation, the 'residual' amount of alkalis were determined as shown in Table 1. Results indicate that the current level of 'residual" alkalis available in the cementitious system, of about 0.4% are in the range of low-alkali content. On this basis, further ASR in the structure can be expected to be considerably limited. However, low alkalinity in cement is not sufficient to guarantee avoidance of ASR occurrence. Past reports are known of ASR occurring with low-alkali cements (Famy & Kostmatka, 1997). Figure 8 (based on South African research data for local reactive aggregates) shows that at cement content in excess of about 440 kg/m^3, there is a real potential for further ASR in this structure. At lower cement contents, the whole future ASR system might be considered innocuous (Fulton's, 2001).

Table 1. Alkali content of hardened cement paste

	UPV (m/s)	Na_2O (%)	K_2O (%)	"Residual" Na_2O_e
Core 1	4125	0.14	0.37	0.38
Core 2	4275	0.13	0.40	0.39

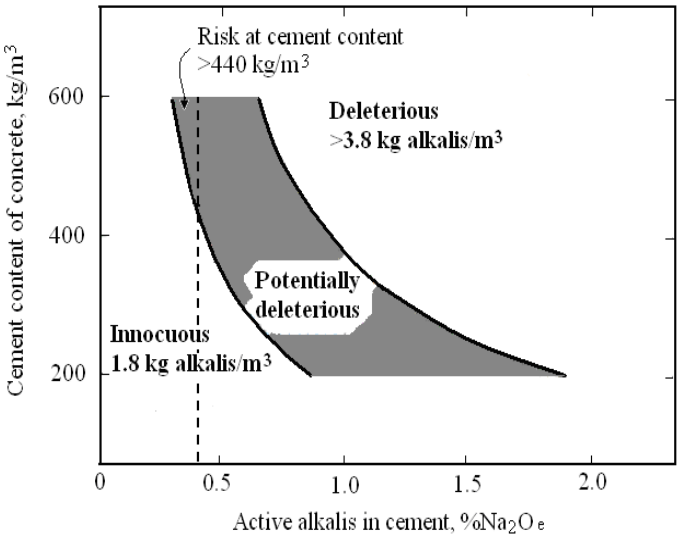

Figure 8. Relation between alkali content of cement and ASR likelihood (Fulton's, 2001)

4 CONCLUSIONS

The foregone laboratory-based analysis for detection of ASR in concrete cores drilled from a deteriorated bridge structure demonstrates the use of two complementary techniques of optical petrography and chemical determinations to sufficiently provide analysis for diagnosis and prognosis that may be of interest in design of repairs. It was found that a moderate level of ASR was present but the risk of

further expansion due to ASR can be considered low, albeit cautiously.

Optical petrographic examination performed on concrete in its original condition by using stereomicroscope, and using thin sections revealed the active presence of ASR in the concrete. The reactive aggregates were identified to be quartz grains. The reactive grains were found to be optically strained, microfractured and microcrystalline, features that are essentially characteristic of ASR prone quartz aggregates. The presence of ASR gel was first observed, albeit inconclusively, by stereomicroscopy on cored concrete surfaces, and also seen in thin sections infilling fractures within internally map-cracked reactive aggregates.

Available alkalis in the cementitious system were found to have been depleted to a present amount of about 0.40%, a low-level not normally likely to promote further extensive ASR damage except at high cement contents.

5 REFERENCES

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